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Publishers page: http://dx.doi.org/10.1007/s42496-023-00149-6 <http://dx.doi.org/10.1007/s42496-023-00149-6>

Aerotecnica Missili & Spazio
https://doi.org/10.1007/s42496-023-00149-6

ORIGINAL ARTICLE

Science and Innovation with Stratospheric Balloons: The Olimpo & Lspe/Swipe Projects

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Received: 5 May 2022 / Revised: 8 February 2023 / Accepted: 10 February 2023

Abstract

The measurement of the Cosmic Microwave Background (CMB) polarization and the spectral distortions produced on this radiation field by clusters of galaxies (Sunyaev-Zeldovich Effect, SZE) are the current frontiers in cosmology. In this paper, we report on two stratospheric balloon experiments aimed to study the research fields mentioned above. OLIMPO is a mm/submm waves telescope, with 2.6 m primary mirror coupled to four arrays of Kinetic Inductance Detectors (KID), centered at 150, 250, 350, and 460 GHz, to match the SZ spectrum, and operating at 0.3 K. The payload, flown in 2018 producing a very successful technology demonstration, includes a plug-in Differential Fourier-Transform Spectrometer. LSPE (Large Scale Polarization Explorer) is a combined balloon-borne and ground-based program dedicated to the measurement of the CMB polarization at large angular scales. LSPE/SWIPE (Short Wavelength Instrument for the Polarization Explorer), the balloon-borne instrument, includes a refractive telescope with a 50 cm optical aperture feeding three arrays of 330 multimode TES bolometers at 145, 210, e 240 GHz. The polarization of the incoming radiation will be modulated by a rotating Half Wave Plate (HWP), that is maintained levitating by an innovative magnetic suspension system. The detectors and the optical elements are cooled at cryogenic temperatures. The cryogenic system is designed to have a duration of 14 days with a flight performed during the polar night, to allow a coverage of a large fraction of the sky. In the paper, we describe the configuration of the two instruments, the modifications to be implemented on OLIMPO for a second scientific flight and the status of the different sub-system for LSPE/SWIPE.

Keywords CMB radiation · Stratospheric balloons · CMB polarization · Spectral distortions of the CMB

1 Introduction

Cosmology and fundamental physics take advantage of precision measurements of the Cosmic Microwave Background (CMB), making these research field very active and competitive.

The CMB is the dominant radiation field of the Universe: it can be observed in any directions in the sub-mm wavelength range and it was produced a few milliseconds after the Big Bang. At that time, the Universe was filled with a uniform hot plasma consisted of protons, neutrons, electrons and photons. In these conditions, the photons could not travel freely across space, but were continuously scattered and thermalized by frequent interactions with the free electrons. Due to the expansion of the Universe, 380,000 years after the big bang, the plasma cooled to the point where electrons were able to combine with protons to form hydrogen atoms: the CMB photons were free to travel until us, carrying important information about the evolution of the Universe. Today, CMB photons form a 2.725 K blackbody spectrum, with its brightness peak at a frequency of 159 GHz. With ground-based telescope, only the long-wavelength side of the CMB spectrum can be accessed, because of the Earth atmosphere opacity. In addition, the atmospheric emission

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Extended author information available on the last page of the article and its fluctuations make it difficult to subtract the contaminating Galactic and extragalactic foregrounds (like the CO lines, the continuum from interstellar dust, the free-free and synchrotron emissions). For these reasons, among others, stratospheric balloon experiments play a unique role in current CMB research, because they allow to carry high-frequency experiments above the bulk of the atmosphere, at an altitude of ~ 40 km, where the atmosphere is no longer a problem for these frequency range.

The mainstream of CMB research today are the search for B-mode polarization, whose detection would represent a confirmation of the cosmic inflation theory, and the measurements of the tiny spectral distortions from a pure Planck spectrum, as those detected in the direction of clusters of galaxies (Sunyaev-Zeldovich Effect, SZE), that would provide a powerful tool for studying the largest structures in the Universe.

The linear polarization of the CMB has three components: the E-mode, correlated with density (scalar) perturbations, emerges from the Thomson scattering between free electrons and a locally anisotropic radiation field; the E–to–B leakage component, at small angular scale, are produced by gravitational lensing of the CMB photons from large scale structures along the path to us; the B-modes, at large angular scales, are generated by the presence of gravitational waves (tensor perturbations) produced during the inflation process. The measurement of r, the ratio between the amplitude of the tensor perturbations and that of the scalar ones, would provide the energy scale of the inflation [1], enhancing our current understanding of the early universe. The current upper limits on r is $r<0{,}032$ at 95% confidence level [2].

The so-called thermal SZE is the inverse Compton scattering underwent by the CMB photons, when crossing rich clusters of galaxies, against the hot electrons ($T\sim10^7$ -10^8 K) of the intracluster plasma. These interaction results in a shift of the CMB spectrum to higher energies, inducing a decrease of the CMB brightness at frequencies below 217 GHz and an increase of the CMB brightness at frequencies above 217 GHz.

Since all measurements integrate signals along the line of sight, there are other components to be considered: the Doppler SZE component, caused by the collective motion of the cluster in the CMB rest frame; the non-thermal SZE component, caused by a non-thermal population of electrons (produced e.g. by the Active Galactic Nuclei present in the cluster, relativistic plasma in cluster cavities, shock acceleration); the emission of dust in our Galaxy and in the galaxies of the cluster; the free-free and synchrotron emission from the diffuse medium in our Galaxy and from the galaxies in the cluster [3]. The physical parameters of the cluster depend on the components mentioned above: it is, therefore, mandatory to remove the degeneracies to retrieve the parameters.

It is clear that in order to properly measure both SZE and B-mode signals, it is necessary to avoid the atmosphere, to cover high frequencies (> 200 GHz) and to perform multi-frequency measurements to separate the contributions of the different components. A space mission is required to perform such science, but stratospheric balloons can play a key role in solving some of the main open scientific questions and in qualifying innovative instrumentation for future satellite missions. Moreover, balloon-borne experiments can be developed at a pace faster than a satellite. The typical time needed to realize satellite missions is about 10–20 years (depending on the payload mass), while the time needed to develop a balloon-borne experiment spans from one year (for small experiments) to few years (for larger ones, like those that study the CBM). In addition, the total cost of a balloon experiment is roughly 100 times less than a satellite mission and the technologies can be tested at laboratory level, without the necessity of qualification level tests, thus leading to less severe requirements.

For all the described reasons and for the privileged observation environment, stratospheric balloons played a key role in perfecting the study of the CMB spectrum, anisotropy and polarization (see e.g. BOOMERanG [4], MAXIMA [5], Archeops [6], TopHat [7], AkCADE 2 [8], PIPER [9], SPIDER [10], EBEX [11] and references therein).

In the following, we describe two balloon-borne experiments, OLIMPO and LSPE (Large Scale Polarization Explorer) designed to perform, respectively, SZE and B-mode measurements.

2 OLIMPO: The Instrument

OLIMPO (see Fig. 1) consists of a 2.6 m aperture Ritchey-Chretien two-mirror telescope, with four Kinetic Inductance Detectors (KIDs) arrays centered at 150, 250, 350, and 460 GHz. The four bands have been selected to match negative, zero, and positive regions of the SZ spectrum. The four arrays are maintained at cryogenic temperatures by a cryogenic system, consisting of a wet LN_2—L^4He cryostat plus a L^3He refrigerator, and designed to provide a hold time of 14 days [12]. The instrument includes a plug-in Differential Fourier-Transform Spectrometer (DFTS), thus allowing the experiment to perform both photometric and spectroscopic measurements. The DFTS has very high throughput, wide spectral coverage, medium to high spectral resolution and excellent rejection of common-mode signals; in fact, it has been designed to measure the brightness difference between a target field and a reference field separated by an offset of about 0.5 deg. In this way, all the overwhelming common-mode sources (instrument emission, residual atmospheric emission, isotropic CMB)

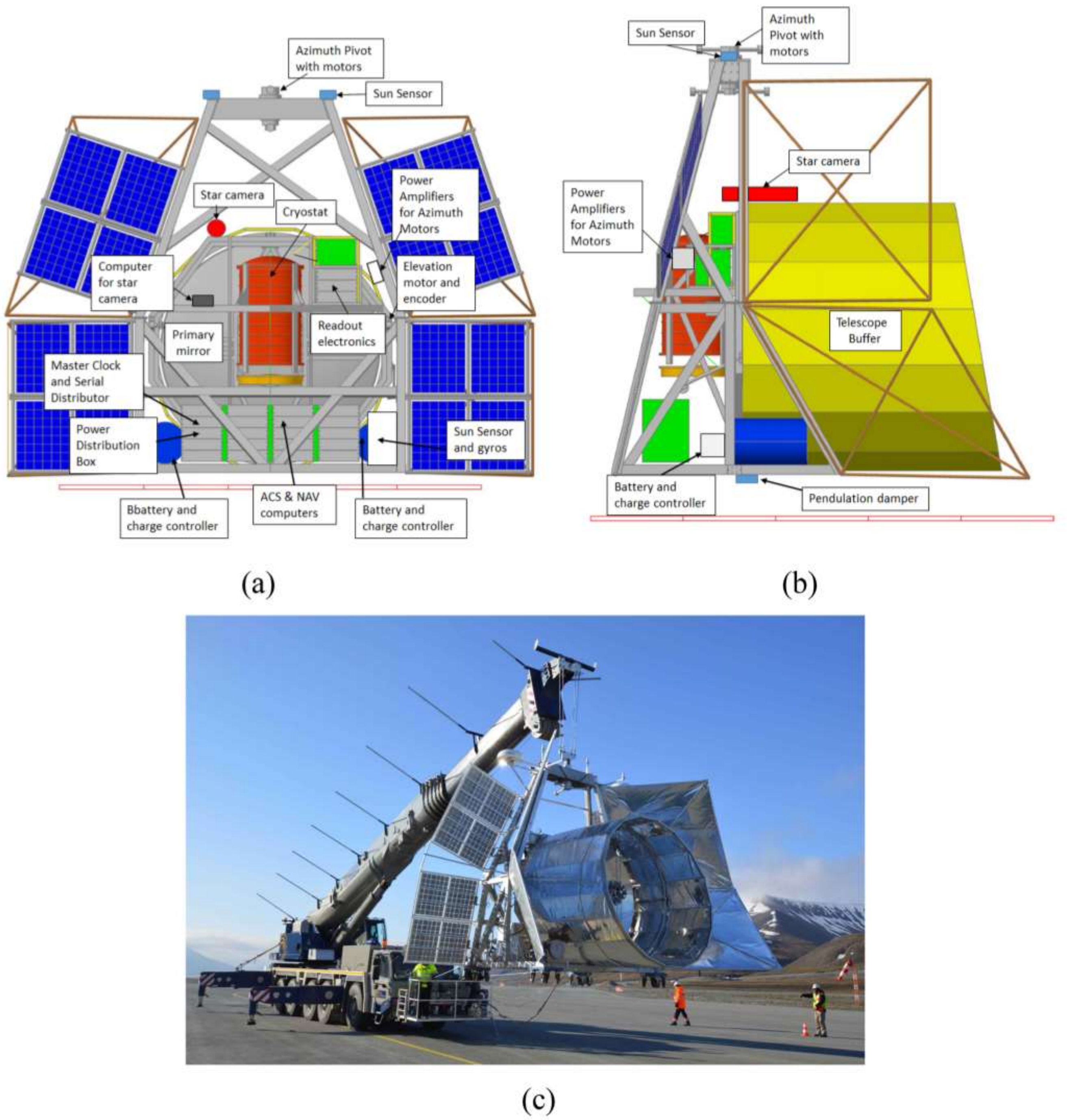


Fig. 1 **a** and **b**: sketch of the OLIMPO experiment with its main subsystems labeled. **c**: the payload hanging from the launch vehicle during an integration test (Longyearbyen, July 2018)

are canceled, and only the anisotropic components (SZE, CMB anisotropy, anisotropic foregrounds) are measured. We have demonstrated experimentally that the Common Mode Rejection Ratio for the OLIMPO DFTS is > 50 dB [13], thus providing a very clean SZE measurement.

2.1 Results from the First Flight and Future Perspectives

The OLIMPO payload had 5 days technological flight in July 2018 [16]: it was launched from Longyearbyen in Svalbard Islands and it was recovered in good conditions in Ellesmere Island, Canada. The decision to terminate the flight after 5 days was made in order to increase the possibility of successful recovery of the experiment, avoiding termination on the Arctic Ocean. The payload was recovered soon after the landing at the end of the same month.

The flight campaign was managed by the Italian Space Agency and the launch was operated by the Swedish Space Corporation. The launch site was selected because of the steady wind circulation in the Arctic summer, which allows to easily predict the trajectories and to avoid thermal instability, due to the constant solar illumination during the entire flight.

The flight demonstrated the excellent performance of the cryogenic system [12] and of the detector arrays [14, 15]: in fact, the focal plane temperatures and the cooled optics reached the nominal temperatures of 295 mK and 2 K and the extrapolated liquid cryogen hold time was 14 days; regarding the KIDs, their noise equivalent power in flight was smaller relative to the one measured in the laboratory, as expected, and data contamination due to primary cosmic rays hits was less than 1% for most of the pixels.

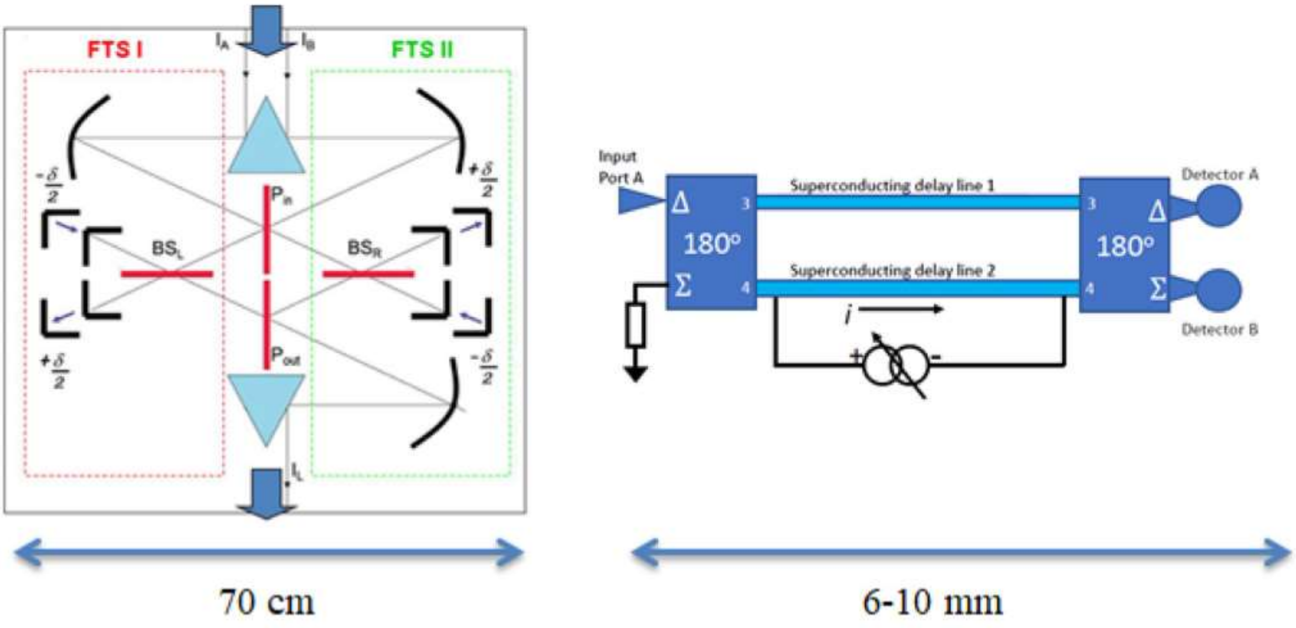
Furthermore, the DFTS was inserted and removed from the optical path several times, and performed as expected. This also allowed to tune the detectors and to demonstrate their dynamics under changes of the radiative background due to the variation of the telescope elevation and the insertion of the DFTS into the optical chain.

After the technological flight, which represents an important step in the Technology Readiness Level advancement of KID technology for future satellite missions, we are now preparing the scientific flight. This is likely to include improved detectors with on-chip spectral capabilities [17].

Usually in an interferometer, like an FTS, the incident beam is split into two and each beam is delayed with respect to the other by one or multiple reflections from mirrors (fixed or moving) and then they are recombined in the detector. The delay, and so the frequency resolution, is proportional to the difference of optical path between the two beams. It is evident that an interferometer needs space to create an appropriate OPD (Optical Path Difference), thus making the instrument voluminous and massive. In the case of OLIMPO to obtain a resolution of 1.8 GHz, it is necessary a maximum OPD of 16 cm. This OPD has been created in a volume of 70 × 70x33 cm (see Fig. 2a) and a weight of 70 kg. In fact, the typical size of an FTS is around one meter, the weight is tens of kilograms and the frequency resolution can range from 150 MHz to 6 GHz. Moreover, another disadvantage of a standard FTS is the necessity of many optical components and mechanisms to move precisely the mirrors are necessary, increasing instrument complexity and risks.

Using superconductive thin films, it is possible to transfer the spectral capabilities on chip, saving mass and volume. This would greatly benefit balloon and satellite missions.

An on-chip FTS is obtained splitting the signal in two identical delay lines with high kinetic inductance: driving



(a) (b)

Fig. 2 **a**: sketch of the OLIMPO DFTS **b**: sketch of an on-chip FTS a small DC current through one of the two delay line the quasi-particles density will change and thus the kinetic inductance, consequently modifying the phase delay in a controlled way. Then, the output signals can be recombined to obtain the interferogram (see Fig. 2b).

With such a device, it is possible to reach very high spectral resolutions (fractions of GHz), because a significant delay can be reached by a small portion of the delay line (~ 1 mm) and with a small amount of current (~ 1 mA DC current).

For the next OLIMPO flight, probably only six on-chip FTS pixels will be allocated in the 150 GHz channel, using the standard KIDs for the rest of the other 13 pixels in the channel.

The main parts of the instrument (telescope, cryostat, focal plane), despite the crash, were recovered in good conditions and possibly reusable for a second flight, with a little refurbishment. Regarding the launch opportunity, the Sapienza team applied to a NASA call for a flight from the McMurdo station in Antarctica with the endorsement of the Italian Space Agency.

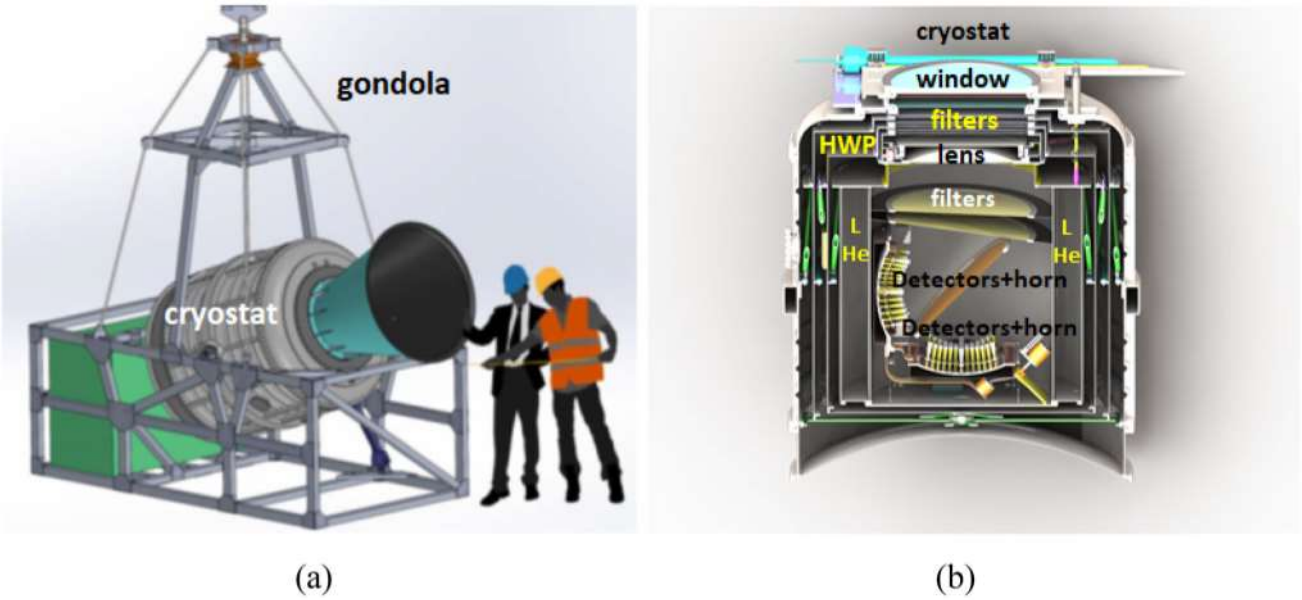
3 LSPE/SWIPE: The Instrument

The goal of LSPE [18] is to measure the CMB polarization to constrain r at a level of 0.015 with a sensitivity $\sigma_r < 0.01$ at 95% confidence level. For these reasons, it is necessary to build an instrument that, differently than OLIMPO, is sensitive not to the radiation total power but to its polarization. In addition, differently to the SZE, B-modes are very tiny signals (fractions of a μK in CMB units), so for this kind of measurements we need two independent polarimetric instruments, to mitigate the instrument systematics, and a multi-frequency coverage to remove accurately the large signals from the foregrounds (synchrotron emission and thermal dust emission). This design would allow to measure r at a level of 0.015, improving the best current upper limit by a factor of about 2 and, thus discriminate among different inflation models. Moreover, taking advantage of the internal polarization modulator and the greatly reduced atmospheric noise, LSPE will cover the lowest multipoles ($l < 100$) corresponding to B-mode polarization produced at reionization, which is not covered by current ground-based experiments.

The two instruments composing LSPE are Strip and SWIPE (Short Wavelength Instrument for the Polarization Explorer). Strip is a radiometer-based telescope operating in the low-frequency range (40 GHz and 90 GHz bands) (see Fig. 4 and 6 in [19]) and it will be installed in Teide Observatory (Tenerife). It will measure the Galactic synchrotron radiation, an important polarized foreground for CMB polarization measurements. SWIPE [20] is a mm-wave polarimeter optimized to operate in the high-frequency range in order to measure the CMB polarization and the polarized foregrounds from interstellar dust. It has been designed to fly on a winter arctic stratospheric long-duration balloon.

In the following, we focus on SWIPE. A general view of the LSPE/SWIPE payload, identifying all the main subsystems, is shown in Fig. 3.

The incoming radiation is focused by a 50 cm aperture refractive lens and modulated at 4 Hz by a cryogenic rotating Half-Wave Plate (HWP), whose rotation mechanism is



(a) (b)

Fig. 3 **a** sketch of the SWIPE gondola and of the cryostat. **b** sketch of the inner part of the cryostat based on an innovative superconducting magnetic suspension system. The two polarization are separated by a polarizer on two focal planes populated by 330 multi-mode TES (Transistor Edge Sensor) bolometers. The choice to have multi-mode sensors is for increasing the sensitivity of the instrument (330 multi-mode sensors corresponds to 8800 single-mode sensors) [21]. The detectors, coupled to the radiation through conical horns, are divided in three bands: a 145 GHz broad-band channel to match the peak of CMB brightness and 210 and 240 GHz narrow channels to monitor the polarized signal from interstellar dust. The detectors arrays, the polarization modulator and the telescope are cooled, respectively, to 0.3 K and about 1.6 K by a ^{4}He wet cryostat and a ^{3}He refrigerator for the last stage. The cryostat is mounted on the gondola, in which also the attitude control system, the power system and electronics are located. The gondola, thought its azimuth pivot, will provide the azimuth spin to perform the scan of the sky.

3.1 Subsystems Current Status

The development of the SWIPE instrument is currently on going. Many subsystems have been manufactured and tested, while other are still under design or fabrication.

Regarding the focal plane, its structure is ready, while the mass production of TES detectors is currently in progress: the first part of the fabrication process (deposition of the absorber) is almost completed. Nevertheless, to proceed with the rest of the fabrication steps, it is necessary to modify the original design to tune some detectors parameters. In fact, tests on the previous prototypes showed that the time constant was too high for our scientific goals (170 ms instead of 30 ms). Golden thermal bonding has been added with the aim to increase the thermal conductance and consequently decreasing the time constant. Now, we are performing tests on different samples to find a trade-off between the two parameters in order to finalize the detector design. To better handle the TES detectors a new detector holder has been designed: it allows to avoid breaking the detectors due to the use of the glue to fix them and to facilitate the thermal bonding.

The detector readout electronics is based on a Frequency Domain Multiplexing (FDM) scheme with a mux factor 16:1, that uses Superconducting Quantum Interference Device (SQUID) and the LC filters. The FDM boards have been assembled and the firmware for basic operation written; the SQUID box has been constructed and tested and the extension of the actual LC filters design from 6 to 16 channels is underway.

Regarding the rotation mechanism, all its parts (the clamp/release system for the magnetically levitating rotor, the superconducting magnets, the rotor permanent magnet and the control coils) have been built (see Fig. 4a); the clamp/release system has been also tested at cryogenic temperatures [22], while the rest has been tested at room temperature. The cryogenic tests will be performed as soon as the cryogenic testbed will be in place. The control electronics of rotation mechanism has been designed and produced, together with a new capacitive system for the position and temperature measurements of the levitating HWP [23].

The engineering study on the telescope lens and its anti-reflection coating is also complete: the lens will be made of high density polyethylene to ensure a good transmittance in the three bands and limited dielectric losses at high frequencies, while the anti-reflection coating will be based on porous polytetrafluoroethylene in order to minimize reflection losses.

(a)

(b)

Fig. 4 **a** The HWP rotation mechanism. The diameter of the HWP is 50 cm; **b** The thick window/NDF movimentation system. The diameter of the thick window is 58 cm

To withstand the atmospheric pressure on the ground, a thick window will be placed in front of the cryostat window. In stratosphere, this thick window will not be necessary anymore, so a movimentation system has been designed and fabricated (see Fig. 4b) to exclude it from the optical path. This system will also host the Neutral Density Filter (NDF), located behind the thick window. The NDF will reduce the radiative background on the ground, in order to allow tests in a stratosphere-like environment, and it will be removed by the movimentation system together with the thick window. We found a thermal-vacuum chamber big enough to contain the system and tests will be performed in the next months.

The cryostat fabrication is almost complete (see Fig. 5a) and will be delivered by April 2023 while the gondola and the azimuth pivot have been already delivered to the integration site (see Fig. 5 b and c).

The frame and the electronics of the two star sensors, necessary for the pointing reconstruction, have been fabricated. Functional tests on the electronics have been performed, while environment tests are scheduled very soon. The on-board computer has been selected, procured and successfully tested in a thermal-vacuum chamber.

The pre-integration campaign, due to COVID pandemic, has been shifted, and it is now scheduled for September 2023.

3.2 Flight

LSPE-SWIPE is designed to fly on a stratospheric long-duration balloon during the (Arctic or Antarctic) winter, because the CMB B-modes signal is very small and a winter flight guarantees to avoid solar irradiation and the presence of the sun in the sidelobes. In addition, it allows to cover a large fraction of the sky by spinning the full payload, thus efficiently exploring the CMB polarization anisotropy at large angular scales. It also contributes to reduce instrument and environment temperature and ensures very stable observing conditions, due to the payload thermal stability and to the low residual turbulence in the atmosphere.

To reach the scientific goals ($r < 0.015$ with a sensitivity $\sigma_r < 0.01$ at 95% confidence level), the measurements have to be acquired for at least 8 days (goal 15 days), maintaining the darkness conditions for about 95% of the time. Moreover, SWIPE has to observe the same (Northern) sky of the STRIP instrument. The best options as launch sites in the northern hemisphere are the Svalbard Islands and the launch facility of the Swedish Space Corporation in Esrange, Kiruna (Sweden). The Svalbard Islands are better for the darkness condition, but the logistic is simpler for Kiruna. For the site selection we have to take into account these considerations and other aspects. The selection is still ongoing.

4 Discussion and Conclusions

OLIMPO and LSPE are crucial cosmological experiments in Italy, both from a technological and scientific point of view. In fact, both experiments, in addition to provide early science in these field of research, contributes to validate technologies and methods for future satellite missions.

This happened in the past, with the BOOMERanG [4], MAXIMA [5] and Archeops [6] balloon-borne experiments, that validated the measurement methods and parts of instrumentations for the Planck mission [24]. With LSPE/SWIPE [19] and OLIMPO [25] is happening again, because their technologies will be used on the LiteBIRD satellite [26], devoted to B-modes, and on the Millimetron mission [27], devoted to study the SZE. Other balloon-borne missions

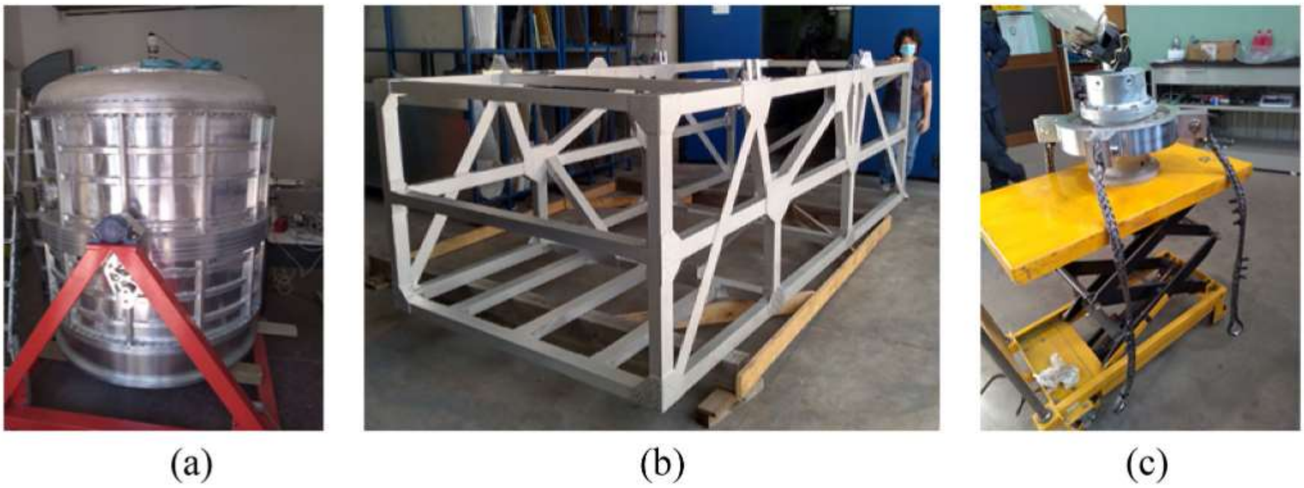

(a) (b) (c)

Fig. 5 **a** The cryostat. The diameter is 1.4 m; the mass is 250 kg; **b** The gondola. **c** The azimuth pivot (like an extension of COSMO [28]) are being designed to measure isotropic spectral distortions and can be used to qualify the instrumentation for the PIXIE project [29] and/or future larger satellite missions within the ESA Voyage 2050 program [30].

Acknowledgements The OLIMPO program has been supported by the Italian Space Agency grants (I-004–07-0 and 2016–4-H.0 and their integrations. The LSPE program has been supported by ASI (grant I-022–11-0 and its integrations) and by INFN (grant LSPE). The launch campaign from Svalbard was supported by ASI (grant 2018–1-M.O) and partially supported by the RSF (grant #19–19-00,499).

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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